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INLETS AND NOZZLES FOR AEROSPACE ENGINES

Technical Evaluation Report on Propulsion and Energetics Panel 38th Meeting on

Inlets and Nozzles for Aerospace Engines

by

D.N.Bowditch and R.Monti

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TECHNICAL EVALUATION REPORT ON PROPULSION AND ENERGETICS PANEL 38TH MEETING

on

INLETS AND NOZZLES FOR AEROSPACE ENGINES

by

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The Proceedings of the Propulsion and Energetics Panel 38th Meeting are published as AGARD Conference Proceedings No.91 – "Inlets and Nozzles for Aerospace Engines"

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I. GENERAL REMARKS

The Propulsion and Energetics Panel of the NATO Advisory Group for Aerospace Research and Development held the 38th Meeting on ''Inlets and Nozzles for Aerospace Engines'' in Sandefjord (Norway) from 13-17 September 1971. The meeting was arranged by the committee under the guidance of program chairman N. F. Rekos.

While the papers in the meeting were limited to discussions of inlets and nozzles, the applications ranged from V/STOL to hypersonic. The majority of papers discussed problems associated with supersonic propulsion systems, with many papers devoted to SST results from the United States and Anglo-French programs. Paper subjects covered test techniques and facilities, experimental results covering the range from small rig tests to flight tests, and theoretical analysis of propulsion system flows. Thirty three papers were presented under five session topics. However, in order to review the main contributions given in the papers, it appeared more appropriate to divide the papers into the four groups used in the text.

II. INLET AND NOZZLE TEST TECHNIQUES

As mentioned previously, the first morning of the conference was spent reviewing propulsion system testing problems covered in a September 1970 meeting of the AGARD Ad Hoc Committee on Engine Airplane Interference in Transonic Testing. These results will be available in more complete form in an AGARD report. Ferri (1)* reviewed the committee conclusions regarding improved testing methods while Jaarsma(2) and Fuhs(3) reviewed current inlet and nozzle testing techniques while pointing out sources of error due to incomplete simulation.

In the area of transonic inlet testing, it was concluded that additional results are needed to define the effect of the downstream airframe on the inlet flow field. Also Reynolds number and scale effects are currently difficult to predict and standard methods should be developed to transfer model results to flight on inlet airframe compatibility, and the drag of boundary-layer diverters, bleeds, etc. This is particularly a problem at transonic speeds where good accuracy is necessary and models must be small to avoid wind tunnel interference. The internal inlet dynamic characteristics are also Reynolds number sensitive and need better definition.

The exhaust nozzle problems fell into two categories. First an area associated with external flow and installation effects and second, an area considering the distorted primary flows from turbofan engines. The latter problem is twofold. Due to the distortion of the primary flow, an ideal thrust is currently difficult to define making nozzle performance hard to evaluate. The distortion also makes it difficult to design an optimum shape for an exhaust nozzle. The interaction of the exhaust nozzle with the external flow at transonic speeds is probably the most serious nozzle problem with scale and/or Reynolds number effects (improper boundary-layer characteristics) causing much of the difficulty. Fuhs pointed out that unsteady boundary-layer separation has been largely ignored and should be given more attention. Another difficult area of model testing is proper simulation of inlet and nozzle flows. Many ways were discussed to get approximate simulation but the most promising of these was turbine-powered engine simulators.

Bergman's paper(22) on An Aerodynamic Drag Study of Jet Engine Nozzles had important implications for exhaust nozzle testing. His results show that the nozzle boattail drag is sensitive to both exhaust jet shape and velocity. At high subsonic speeds, as jet pressure ratio increases to about 1.5, drag decreases as a cylindrical jet is formed. Then as a pressure ratio of 2.0 is approached, drag increases as the flow of the jet approaches the sonic speed. The higher jet velocity pumps the external flow thereby giving an effective plume shape of a converging cone. Further increase in pressure ratio expands the jet plume cross section reducing boattail drag. Bergman discusses the implication of these results as they apply to flow-though nacelle testing and solid boundary jet simulators.

Masure(4) reviewed the methods used at ONERA for accurate measurement of model nozzle performance. Sonic nozzles for flow measurement are described, along with the necessary corrections for boundary layer, throat flow distortion and compressibility. A nozzle test facility was described. Some results were presented which indicate primary nozzle flow coefficient variation with convergence angle and optimization of the spacing of a conical ejector nozzle. The optimum spacing was shown to be dependent on the available secondary air pressure.

Jean Claude Ripoll and Jean-Bernard Cocheteux(5) described current altitude engine test facilities in France and the proposed improvements for 1975. The authors also described use of the facility for subsonic and supersonic free-jet testing. Associated nozzle performance and nozzle acoustic facilities were also described.

An interesting paper was presented by J. C. Ascough(6) describing full-scale thrust performance tests on the Concorde exhaust nozzle. An initial comparison of full-scale and model data indicated that thrust was 1.7% less for the full-scale test. While part of this difference could be accounted for by geometry differences and measurement errors, about 0.7% was still unexplained. Two hypotheses were proposed. One hypothesis added potential consistant measurement errors to explain the flow coefficient and performance discrepancies. A second hypothesis assumed that leakage was responsible. Both appeared feasible, but discussion after the presentation favored leakage and possible γ effects as the probable cause.

Both exhaust nozzle and inlet test techniques were discussed in Bowditch's paper(7) reviewing work at the NASA-Lewis Research Center. Comparisons between wind tunnel and flight data from an F-106 program demonstrated transonic wind tunnel interference problems. The effect of Reynolds number on nozzle boattail drag was also discussed. To evaluate the ability of one inlet to disturb another, it was shown that good simulation of large-scale transients such as engine surge must be combined with proper airframe simulation. Lesser simulation can predict too small an interaction. The role of dynamic distortion in explaining engine surge occurrence was also discussed.

*Numbers in parentheses refer to the papers listed at the end of this report.

III. V/STOL INLETS AND NOZZLES, THRUST VECTORING

V/STOL inlet and nozzle configurations are quite different from those of the conventional airplanes; a number of typical problems have been considered by papers falling into this group, in particular five papers discuss nozzle and inlet distortion, augmentor wing and non-conventional ways of controlling flow distortion at the compressor face; other two works deal with thrust reverser and with thrust vectoring.

Schwantes(15) and Tyler and Williamson(8) examine, for different purposes, jets from V/STOL nozzles, impinging on a flat surface in the presence of a cross wind. Schwantes(15) examines in detail the effect of: 1) gasdynamic conditions (temperature and Mach number) on free jet spreading and wall jet characteristics and 2) cross wind velocity on separation of the wall jet and on the possible recirculation (and debris reingestion). Conclusion of major interest for V/STOL airplane operation are that for a single jet, in hovering, no recirculation seems to appear in the absence of wind and that the Mach number (and not the velocity) greatly influences the separation point location (when the Mach number is larger, the point of separation moves wind-ward).

Tyler and Williamson(8) made a number of wind tunnel tests with high powered V/STOL models, to establish the optimum model position, the jet characteristics and the wind tunnel speed range within which the experimental aerodynamic data remain meaningful. An incipient stagnation condition is defined as the condition at which two stagnation points appear on the wind tunnel wall where the jet impinges and a portion of the wake flows upstream to roll up into a stable vortex. These conditions identify the tunnel flow breakdown (meaningless data): The incipient stagnation parameter which satisfactorily correlates the results is simply $h/D\sqrt{g_o/g_j}$ whose critical values are function of α. When comparing these conclusions with those of paper 15 a discrepancy seems to appear, since the incipient stagnation parameters would depend only on dynamic pressure ratio and not on Mach number.

Lewis and Prechter(10) study different geometries for a clamshell target-type thrust reverser as a means of obtaining braking force from a jet engine. A number of geometrical parameters have been investigated such as the reverser bucket width, height, distance from the nozzle exit, end plate depth, sweep angle and wrap angle. The effect of the target shape and position on the nozzle discharge coefficient is discussed. The authors concentrate on the problem of hot gas reingestion due to the efflux impinging on the ground. The better configurations required reverser rotation or displacement, which reduced the amount of jet impinging on the ground.

McGregor(12) examines the very interesting problem of boundary layer control in air inlets of V/STOL aircraft. As the author points out, the BLC by blowing has not received too much attention for conventional aircraft because the weight and complications involved with this type of control. The intake blowing BLC requires blowing flow rates that are only of the order of 1-2% of the engine mass flow rate. Suction bleed and slot blowing BLC have been examined and compared. If the slot blowing system is adopted in the intakes of a VTOL strike aircraft, instead of the suction bleed, the maximum thrust can be increased by 1 to 2% and a considerably lower level of flow distortion at the entry of the compressor can be achieved.

Whittley(13) analyzes some problems which arise in connection with the augmentor wing concept for a V/STOL airplane. The augmentor primary nozzle is examined together with wing ducting, choice of the engine cycle and noise attenuation. A number of project studies, based on wind tunnel tests, show the advantages of the powered lift concept as applied to V/STOL operation with respect to low noise, safety and short field performance.

Paper(9) by James deals with a subject which is not exactly related to inlets and nozzles for Aerospace Engines: the benefit of having a vectored thrust in air combat is examined by a manned air combat simulator. Three types of aircraft have been simulated: 1) conventional fighter, 2) a vectored thrust version of the conventional fighter and 3) a vectored thrust version of the same conventional fighter plus a 1500 pound weight penalty. Two types of scoring were used, in both of which the vectored thrust version was well above the conventional aircraft (also the weight penalized version behaved better than the conventional aircraft). No losses, when vectoring the thrust, were assumed to exist. There is no doubt that thrust vectoring may give very important additional manouvering capabilities to the pilot.

IV NOZZLE DISCHARGE: MIXING, DRAG, INTERFERENCE

Five papers deal with this subject; specifically problems related to boattail pressure drag, to optimum afterbody geometries, to double flow problems and to best nozzle configurations for V/STOL applications have been examined.

Paper(23) studies in detail the effect of the nozzle discharge on boattail drag and on base pressure at supersonic speeds; the subject is related to that of paper(12), which examines afterbody geometries at given flight conditions and the external boattail shape, and to that of paper(22), which deals with jet simulation for model testing.

As the exit nozzle pressure increases above a certain level, substantial overpressures can feed forward, decreasing the boattail pressure drag, Stoddard(23) defines a critical base pressure as that pressure level required to separate the terminal shock wave; above this level the boattail pressure substantially increases. The paper attempts a very useful and simple correlation between nozzle geometry and nozzle base pressure; this last, together with the knowledge of the critical base pressure, permits computation of the boattail drag. Comparisons are made between boattail pressure drag for both converging and converging-diverging nozzles; the main conclusion is that the convergent-divergent nozzle (or similar sophisticated shapes) may not be better then the simple convergent nozzle, after proper accounting of the boattail drag reduction has been done.

A very extensive parametric study has been performed by Hardy(11) on the afterbody geometry. Convergent and convergent-divergent geometries were considered for the primary jet nozzle; in both cases the primary jet discharges in a convergent-divergent duct. The parameters which have been considered are: pri-

mary nozzle discharge area, throat area for the main duct, shapes and angles of ducts and distance between primary nozzle exit and main duct throat, shape of the cross section at the duct exit and the effect of high temperature gas discharge. To these parameters others are added when examining the convergent-divergent primary nozzle (angle, exit area and length of the divergent part of the primary nozzle). Systematic correlation of the experimental results have been made with theoretical calculations, which use the characteristics method for the primary jet, and the isentropic assumptions for the secondary flow: the agreement seems to be always satisfactory and the author concludes that the afterbody geometry can be almost completely defined on those theoretical bases.

The paper by Paulon(31) studies in detail the discharge characteristics of a supersonic jet (primary flow) in a subsonic jet (secondary flow) in a constant area duct. A two dimensional and an axisymmetric geometry have been experimentally tested. Static and total pressure surveys have been made mainly in the outer region (secondary flow) and schlieren pictures have been taken of the two dimensional mixing zone. The experimental results have been compared with one dimensional and with characteristics theories. The overall performance of the ejectors in both cases (two dimensional and axisymmetric) are very well predicted by the one dimensional scheme; the agreement is justified by the rather large aspect ratio of the constant area duct investigated. The details of the jet geometry are of course not satisfactorily predicted by one dimensional theories; characteristics theory for perfect (non viscous) gas gives more information on jet geometry but if viscosity is not taken into account the extension of the mixing region and the velocity (and temperature) profiles cannot be properly predicted.

A time dependent technique for the solution of a double flow nozzle, has been presented by Osnaghi and Macchi(27). A numerical program has been prepared based on the method of characteristics. An initial steady flow condition is assigned which is perturbed by changing the geometrical boundaries until the geometry reaches the final configuration; at this time no further perturbations are imposed and the flow will evolve asymptotically towards steady flow which represents the sought solution. The main advantage of this technique is that one only deals with hyperbolic equations and therefore may adopt the methods of characteristics for any kind of flow (subsonic, transonic and supersonic) which avoids the convergence and the stability difficulties associated with the elliptic equation numerical solutions. The method is also able to analyze the history of the flow development in an unsteady situation.

The very peculiar requirements of a V/STOL nozzle discharge can be met by rapid mixing nozzles, as illustrated by Chester(14). The main problems related to hot gas discharge by a near vertical engine in proximity of ground are: 1) ground erosion and reingestion of hot gases and solid particles 2) thermal damage of the airframe and under carriage 3) noise level. Previous works indicate that the ground dynamic pressure is the most important parameter for ground erosion. A substantial dynamic pressure reduction can be obtained by means of a rapid mixing nozzle (typical geometry tested was a 9 outlet nozzle with an airflow inlet area/nozzle exit area ranging from 2 to 1). This kind of nozzle strongly alleviates problems 1 and 2; the noise reduction does not seem to be substantial, for the examined geometry. However when considering the performances of the rapid mixing nozzle a non negligible thrust penalty appears, mainly due to internal losses (typical thrust loss are 3% plus 1.5% due to base pressure changes).

V. INLET ENGINE MATCHING AND COMPATIBILITY

A comparison of papers by Tjonneland(18) and Larsen(21) describing the Boeing SST inlet and control with papers by Ashwood(19) and Leyman(20) on testing the Concorde inlet provides interesting results. The mixed compression inlet required for a Mach 2.7 cruise aircraft is much more complex than the all external Concorde inlet. The Concorde inlet has only two movable ramps, one slot bleed, and a single bypass door. The Boeing inlet has four cowl doors, a translating centerbody with translating bleed, four bypass doors, a cowl bleed that is turned off when the cowl doors open, vortex valves to provide inlet stability, and a much faster control system than Concorde. Because inlet unstart is so close to peak operation for the Boeing inlet, its control must allow much smaller errors than Concorde where a larger stable operating range is available. This requires a faster control for the Boeing inlet, as well as crossbiasing of several signals and signal schedules with centerbody position. Tjonneland also described some sophisticated inlet design tools to determine accurate inlet flows. These were computer programs for predicting the inviscid flow field, its interaction with the boundary layer, and the general health of the boundary layer. The apparent quality of these prediction methods was an indication of the effort required to make such a mixed compression inlet operate well throughout the flight range.

Leyman, in his paper on Concorde experience, pointed out that while extensive tests were made on the inlet engine combination, the inlet control required considerable modification during flight test. A major cause of that was the inability to properly simulate the installed environment of the inlet. The full scale wing boundary layer appeared to affect inlet control pressures. Therefore, it was necessary to obtain final inlet control schedules from full scale flight testing.

In his paper(25) Surber reviewed the results of three Air Force basic research programs concerning inlet performance during maneuvering flight. Results from the Taylormate Program indicated flow fields that could be expected about forebodies at angle of attack and yaw. Half axisymmetric and two-dimensional inlet performance in representative flow fields was also presented. This data was complimented by results from separate subsonic diffuser testing. Also, preliminary results from tests of 0.125, 0.228 and full scale models of the RA5C inlet were compared to investigate scale effects on inlet distortion data. Some general conclusions from the programs governing inlet development and test techniques were given.

Results of a NASA flight program investigating inlet-engine compatibility were presented by Burcham(24). Both steady state performance and dynamic distortion results were presented. He showed that it was necessary to sample the distortion with high-response pressure transducers at a rate of about 400 samples per second in order to measure distortions that correlated well with engine surge. With such instrumentation, excessive distortions lasting as little as three milliseconds (one half rotor revolution) were found fifteen milliseconds before engine stall. A duct resonance was also observed which interacted with the inlet shock system to provide a cyclic change in inlet distortion.

A discussion of an engine design procedure for assuring inlet engine compatibility was presented by Ellis(26). He showed that it was necessary to allot surge margin for a number of expected engine operating conditions. Several of the requirements were due to component interactions (i.e., fan and compressor), Reynolds number effects, flow distortion and temperature distortion. As part of his distortion discussion, he presented dynamic distortion data indicating instantaneous distortions significantly in excess of the steady state value. This was the third paper (in addition to Burcham and Bowditch) showing the significance of dynamic distortion in inlets.

Stanley(29) presented experimental measurements of the static pressure distortion at the face of a centrifugal compressor being fed by a radial inlet. This static pressure distortion represents a deviation from the axial uniform flow for which the compressor was designed. The flow measurement were compared with an analysis which was presented by Gallet(16). The analysis could be used to improve the inlet shape, or provide a description of the flow at the compressor face which could be used for compressor design. Another flow analysis for prediction of the inviscid flow distortion at the compressor face was presented by Ledoux(28). The method was also compared with test data.

The only hypersonic inlet discussion was presented by Leynaert(30) who treated the starting problem of mixed compression inlets. He showed that flow separation creates a multiple shock flow field that makes starting possible at higher contractions than simple normal shock theory predicts.

A novel concept was presented by Dettmering(33) which would replace a normal inlet with a rotating stage to decelerate the flow. The rotor can remove energy from the flow as it decelerates. The amount of energy can be varied from zero to a significant amount depending on design and operation. Several uses for such energy are considered. The analysis of such a rotor is in the initial stages of evaluation and many problems such as matching and stress have not yet been evaluated.

VI. CONCLUSIONS

1) The scope of the conference was fairly large for the conference size. A more focused scope, such as the high temperature turbine or noise and sonic boom meetings, would be more desirable.

2) Many problems still exist in transonic testing for propulsion system integration. While propulsion simulators and new incremental test techniques have improved the accuracy of aircraft performance prediction, more work is required. This is particularly true in the area of viscous effects.

3) Flow analyses presented at the meeting demonstrated good capability for predicting well-behaved internal flows. Their use in design should increase and will replace some current test requirements.

4) The dynamic aspects of inlet distortion must be considered when determining inlet-engine compatibility.

5) The development of an efficient SST inlet-engine system is a complex problem requiring consideration of many aspects which are difficult to study in the size of facilities currently available. Therefore, the development of system performance and control should be expected to extend into the flight testing phases. Allowance should be made for changes to the system at this late stage of development.

VII. RECOMMENDATIONS

1) A more limited program scope would be desirable for a meeting of this size. If the scope remained similar, a larger meeting with concurrent sessions would be an improvement.

2) Interpreting at a bilingual meeting is obviously difficult, particularly considering the peculiarities of technical jargon. Therefore, it is easy to become interested in a paper during a presentation but not fully understand the results. It is not possible, now, to go back and read every paper unless you are fluent in both NATO languages. Therefore, it would be very desirable to have some form of interpretation of the paper available. At a minimum, this could be a typed version of the interpretation given during the paper. This has obvious inadequacies but is much more than is now available.

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25.	L. E. Surber and D. J. Stava	Supersonic Inlet Performance and Distortion during Maneuvering Flight
26.	S. H. Ellis	Inlet-Engine Compatibility Analysis
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Papers referenced above are published, with the same reference numbers, in AGARD Conference Proceedings No. 91 - "Inlets and Nozzles for Aerospace Engines".

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